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Time-Domain Tools for the Investigation of Gain-Quenched Laser Logic

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Time-Domain Tools for the Investigation of Gain-Quenched Laser Logic

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Abstract

Integrated all-optical logic gates that exploit the optical gain quenching effect in laterally optically pumped semiconductor multi-section edge-emitting lasers (SMEELs) are described. An accurate 2D time-domain (TD) model was implemented to investigate the gates' gain, modulation depth, and speed.

Summary

Gain Quenched Laser Logic (GQLL) offer the potential of integrating several processing functions on the same chip and has many applications for all-optical high-speed switching. Lasers with optical gain control capable of routing and logic functions[1,2,3] have been demonstrated via the gain quenching effect[4]. In an inverter gate the laser output power is quenched when an optical input signal laterally coupled to the laser (control region) is high. NOR and NAND gates are achievable by adding other arms[5]. The basic configuration of a GQLL device is schematically depicted in Fig. 1. The Boolean completeness of this technology, the recent achievement in high laser modulation bandwidths, and the possibility of integrating lasers and passive waveguide interconnects progress using standard microelectronics fabrication techniques[6], makes GQLL the basis for a high-speed photonic logic family.

Numerical Models

Several models have been developed for analyzing laser nonlinear differential rate equations, but they are often reduced to a lumped parameter treatment or are implemented in the steady state rather than the transient regime, particularly in the case of optically quenched lasers[7]. Given the promise of this technology, accurate TD modeling tools are important to minimize design cycle time and cost.

We developed a suite of simulators for the analysis and design of SMEELs. We have developed lumped parameter, 1D, and 2D codes and validated them against existing results. [8, 9]

Here we focus on our 2D model, solved using an FFT based BPM in conjunction with the method of characteristics[10], which includes multiple controls, multiple wavelengths, gain saturation, a stochastic model of amplified spontaneous emission, and spatial hole burning, through carrier diffusion and multimode analysis.

Starting from the scalar wave equation, we assume fields of the form

$$E(x,z,t) = \psi^{+}(x,z,t)e^{i(\omega t - k_0 n_0 z)} + \psi^{-}(x,z,t)e^{i(\omega t + k_0 n_0 z)}$$

Using the slowly varying envelope approximation yields

$$2ik_0\left(\frac{n^2}{c}\frac{\partial\psi^{\pm}}{\partial t} \pm n_0\frac{\partial\psi^{\pm}}{\partial z}\right) = \nabla_{\perp}^2\psi^{\pm} + k_0^2(n^2 - n_0^2)\psi^{\pm}$$

The method of characteristics allows us to combine the partial derivatives in time and z to obtain

$$\frac{d\psi^{\pm}}{dz} = \frac{\pm 1}{2ik_0 n_0}[\nabla_{\perp}^2 + k_0^2(n^2 - n_0^2)]\psi^{\pm}$$

These can be solved using an FFT based BPM solver.. We can model gain as either a variation in the imaginary part of the index of refraction, or add it in as an additional separate factor. Carrier density is modeled at every active simulation pixel in the (z,x) plane as follows

$$\frac{\partial N}{\partial t} = \frac{\eta J(z,x,t)}{ed} - AN - BN^2 - CN^3 - PG(N) + D\frac{\partial^2 N}{\partial x^2}$$

Carrier density at a computational pixel is gained through current injection, lost due to various decay mechanisms, and may be gained or lost due to diffusion and interaction with the photon density of the left and right going scalar field envelopes.

GQLL Gates

An investigation of the parameter space was carried out to determine the inverter modulation efficiency (level restoring), gain (fan-out), and time response (clock-rate). We observed that the best gain and modulation depth are obtained using long control regions, wide lasers, and operating close to threshold, with a control power close to the unquenched power. We also verified that optical quenching is a particular case of gain-lever effect.[11] We have shown that although GQLL gates are possible, those with gain greater than one are not feasible. For example a wide laser (>10μm) requiring high current (>10mA), would do the job[12], but a microcavity (L=16μm) with very asymmetric mirrors reflectivity (1:66), would require very high current densities in the control region.

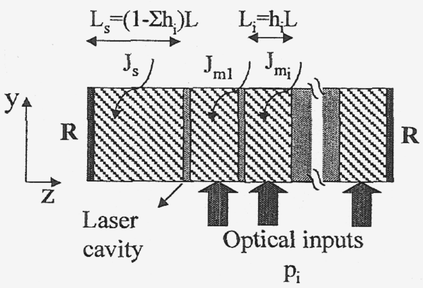

Fig. 1 Scheme of a SMEEL.

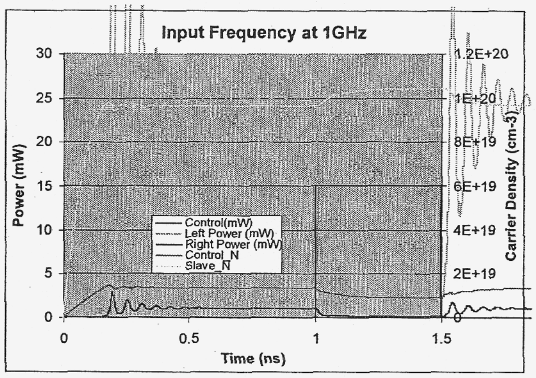

Fig. 2 Output powers and carrier densities for a microcavity laser. A Gain >1 is observed for the low reflectivity facet.

NOR gate behavior is demonstrated in Fig. 3. In the main window the laser running longitudinally is visible together with two lateral input waveguides. Once the laser has reached its steady state, the controls are applied. When two controls are turned on simultaneously a stronger modulation depth is induced.

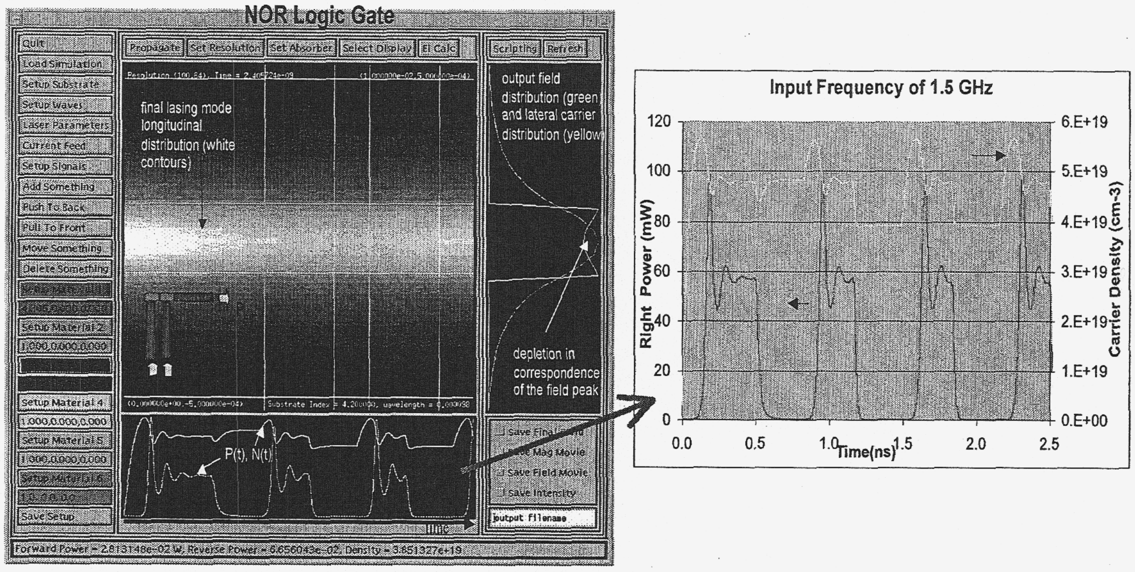

Fig. 3.C++-based Graphical User Interface for 2D model. Central window: final longitudinal field distribution. Lateral window: output field distribution (green) and lateral carrier distribution (yellow) showing spatial hole burning. Bottom window: lasing power and average carrier density as a function of time.

We currently believe nonlinear effects are responsible of the inverter behavior with high gain observed at currents much higher than threshold[3]. We are expanding our code to include free-carrier absorption effects and polarization dependence, which will be described in future communications.

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